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From cradle to grave? On optimal nuclear waste disposal☆

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ABSTRACT

This paper analyses socially optimal nuclear plant operation and nuclear waste management. Two waiting rules are derived: the first characterizes the optimal continuation of electricity production, and the second gives the optimal nuclear waste disposal date. Both rules balance the cost and benefit of either continuing production or delaying waste disposal into a deep geological repository. In addition, multiple regulatory options are investigated. The optimized waste storage and disposal cost forms the payment that should be collected from the nuclear power firm into a nuclear waste fund. The properties of this payment and other regulatory options including a tax to be paid at the shutdown date of the plant are investigated, and it is shown that the money can be collected by a plant-specific constant fee targeted at firm's profit or output. Numerical illustration shows that waste disposal to a deep geological repository is a cost-minimizing solution only with very low interest rates. For interest rates above one percent it is optimal to store the waste in an on-ground storage facility in perpetuity.

1. Introduction

The disposal of spent radioactive nuclear fuel and waste has been a problem since the beginning of the Atomic Age.[1] A nuclear power plant generates a large quantity of electricity from a small quantity of fuel input, but simultaneously the plant produces nuclear waste as a side-product. Spent fuel and nuclear waste are highly toxic to living organisms and must be isolated for very long time periods. Finding an economically, politically and technologically feasible solution for waste management has proven to be a difficult task as shown for example by the U.S. experience (Blue Ribbon Commission, 2012). The need to find a solution becomes even more pressing in the future due to climate change mitigation targets, which may require extending the operational life-times of the existing plants and major new investments to nuclear capacity, which results in additional nuclear waste. Given the current and future importance of nuclear waste management, this paper aims to contribute to the relatively limited economic literature on nuclear power production and waste management by analysing a model where the plant shutdown and waste disposal dates are chosen optimally. The model emphasizes the cost structure and waste stock properties and suggests different options for regulation to guarantee that sufficient funds are collected for future waste management.

Research questions. First, when is it optimal to close the nuclear plant given that the waste must be stored in an (interim) storage facility and eventually disposed of in a deep geological repository?[2] The closure or shutdown decision for a nuclear plant involves the revenue and operating costs of the plant, but also costs related to the maintenance of the plant and storage of the spent nuclear waste. In addition, continuing plant operation produces more waste to be disposed of, which may have an influence on the shutdown decision, and on the regulation needed to collect the funds for waste management.

Second, what is the optimal date to dispose the waste into a geological repository? Choosing the disposal date involves a trade-off between

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[1] Isard (1948) is the first (to our knowledge) to consider nuclear power from the economic point of view, and already he points to "the possible problems of transporting fissionable and radioactive materials and of disposing of radioactive waste materials" on page 223.

[2] Interim storage means storing the waste either in a wet or dry storage facility on ground and disposal means the disposal of the waste into a deep geological repository.

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the storage and disposal costs that is due to the waste properties. Radioactivity and the related heat production of the waste are high during the initial years, which means that disposing it to a deep geological repository is too costly. Therefore it may be beneficial to delay the disposal and to pay the storage cost for some time period after which the waste is disposed of.

Third, how large is the total post-production waste management cost? Calculation of this cost gives the amount of money the nuclear power firm should have for waste management and it also forms the total deposit to a possible nuclear waste fund. To calculate this sum, the regulator needs information on the optimal operation and waste management of the plant.

Fourth, when and how should the monies be collected from the firm? As the plant generates no revenue after shutdown and as the waste disposal occurs possibly decades after shutdown, it is important to analyse the collection of the monies from the firm. In practice the monies are often collected based on the electricity output, like was done in the U.S. (Blue Ribbon Commission, 2012) or is done in Sweden (European Commission, 2017), but setting the fee at the right level requires information on the (optimized) total waste management cost, which is studied here.

These questions are analysed with a two-stage model, where an electricity and waste production stage is followed by a waste storage and disposal stage. Waste management costs, including waste storage and disposal costs, are assumed to depend on the decay heat generation (radioactivity) and mass of the waste.[3] The on ground storage costs mean the costs of storing the waste in a wet or dry storage facility, and the disposal costs include the construction costs of the deep geological facility and the encapsulation and transportation costs. The nuclear power plant is run at constant full capacity and generates revenue during the production stage. The regulator chooses the shutdown date of the production stage while taking into account that continuing plant operation produces more waste. The waste storage and disposal stage begins after shutdown and the regulator chooses the waste disposal date. These choices are characterized by two rules, one for the production continuation and the other for delaying the disposal. The optimal dates together with the cost structure and the physical waste properties determine the total post-operation waste management cost and the waste management payment that is plant specific. These analytical results are illustrated by a numerical application which shows that deep geological disposal of the waste is a cost-minimizing solution only with very low interest rates of less than one percent. This seems to suggest that cost-minimization is not a sufficient reason to opt for geological disposal, but that indefinite on ground storage should, in fact, be seriously considered as an alternative to it unless the use of a very low social discount rate is justified.

2. Background, literature review and contribution

Background. The average age of nuclear reactors in the European Union is 29 years and the original life-time of the 129 operating reactors varies from 30 to 50 years (European Commission, 2017). Currently the EU has about 80 000 tonnes of spent nuclear fuel stored at the reactor sites.[4] Contrary to the nuclear waste fund used in the U.S., the member states of the EU have been responsible to set-up proper mechanisms to collect funds or other guarantees to be used for nuclear power plant decommission and waste management.[5] For example in France, EDF is responsible for the waste management and will set aside 23 billion euros, which together with interest it believes to be sufficient to cover the estimated 54 billion decommission and waste management bill (Dorfman, 2017). However, some experts say that in France as in other European countries there are insufficient resources to guarantee decommission of the plants and proper waste management (Dorfman, 2017; Chestney and De Clercq, 2015).

The amount of spent nuclear fuel in the U.S. was approximately 79 000 tonnes in 2017 and this amount grows by 2 000 tonnes per year (Wealer et al., 2017; Blue Ribbon Commission, 2012). The U.S. strategy to store and dispose spent nuclear fuel has been a costly failure. According to the report for the Secretary of Energy (Blue Ribbon Commission, 2012), the Nuclear Waste Policy Act of 1982 and its amendments in 1987 offered the nuclear companies a trade in which they agree to pay 0.1 cents per produced kWh to the Nuclear Waste Fund in exchange for the promise from the Department of Energy (DOE) to take over the spent nuclear fuel from the companies by the year 1998, and dispose it to a suitable site such as Yucca Mountain. The idea was that the polluter pays, and that the fund would be isolated from federal budgetary considerations. But after the failure to find a location for the deep geological repository in Yucca Mountain or elsewhere, the DOE failed its promise even though the companies, or their customers, had paid the required fees. This has lead to a series of lawsuits against the DOE which resulted in sizeable compensations paid from the federal budget (thus essentially by the tax payers) to the companies.[6,7] Currently the spent fuel is stored at the reactor sites, which can be risky and therefore the re-opening of the Yucca Mountain repository is seen as a relevant part of nuclear waste management programme (Schaffer, 2011). However, the fate of the commercial nuclear waste in the U.S. is an open question.

The plans to open a deep geological repository for nuclear waste from commercial nuclear plants have progressed furthest in Finland and Sweden, but the repositories are not yet open.[8] In Finland, the repository is being built and will house all of the country's nuclear waste from the existing plants and from Olkiluoto 3 plant, which is under construction. The disposal is planned to commence in the mid 2020s. The purpose of the facility is to isolate the waste from the society and ecosystems by different means: the waste is packed into copper capsules, surrounded by bentonite clay and placed into the bedrock at the depth of 400 m. Before disposal the spent nuclear fuel is stored in water in pools, which cools the waste. The nuclear waste management in Finland, including storage and disposal, is expected to cost about 6.5 billion euros (Ministry of Employment and the Economy (Finland), 2015).

Literature review and contribution. Ahearne (2011), Davis (2012) and Lévêque (2015) give recent overviews of the challenges nuclear power faces as an energy source including high construction costs, strict safety regulations and various externality related problems like nuclear waste, possibility for accidents and proliferation. A typical view on spent nuclear fuel, like the one expressed by Lévêque, is that as the disposal cost is realized decades after the plant closure it has only a

[3] The possibility of accidents and fallout risks are not modelled.

[4] At the end of 2010 there were 53 300 tonnes and this number grows by 3 200 tonnes per year (European Commission, 2017).

[5] Globally, 147 reactors have been shut down but only 16 of them have been decommissioned (European Commission, 2017).

[6] DOE's estimate at the beginning of this decade was that the compensations add up to almost 21 billion dollars by 2020 assuming that the DOE fulfils its promise to the companies by then. Moreover, "*a programme that was intended to be fully self-financing now has to compete for limited discretionary funding in the annual appropriations process, while the contractual user fees intended to prevent this from happening are treated just like tax revenues and used to reduce the apparent deficit on the mandatory side of the federal budget*" (Blue Ribbon Commission, 2012, page 72). That is, the Nuclear Waste Fund was not isolated from budgetary considerations.

[7] The fee has not been collected since 2014, but according to the auditor's report the Nuclear Waste Fund contained 44.5 billion U.S. dollars in 2017 (Department of Energy, 2018b).

[8] The only open repository is in Carlsbad, New Mexico, but it is used to dispose waste from military programmes. The total sum of liabilities related to this class of waste in the U.S. is around 494 billion dollars (Department of Energy, 2018a).

small effect on the present total cost of nuclear power and therefore spent nuclear fuel is of second-order of importance. This view neglects the fact that the total cost of waste storage and disposal is high even in a country like Finland with a small nuclear fleet, and the payments to the nuclear waste funds must be collected in order to prevent the cost from rolling to the future tax payers. The cost depends on how long the plant is run and when the waste is disposed of, but there are only a few papers that model optimal shutdown decision of nuclear power plants or optimal nuclear waste storage and disposal to which the current study focuses. The study offers to our knowledge the first economic analysis of optimal nuclear waste management from cradle to grave.

Loubergé et al. (2002) model the choice to switch from surface storage of nuclear waste to deep geological storage. In their model the amount of nuclear waste at the beginning is exogenously given and the surface storage (or interim storage) cost and disposal cost of the waste are independent of the radioactivity (heat generation) and the mass of the waste. In the current model the amount of nuclear waste is optimally decided as the nuclear power plant is operated and the storage and disposal costs depend on the heat generation and mass of the waste. Loubergé et al. (2002) have in their model an element that is missing from the current one, namely the stochastic costs related to accidental releases of radioactivity. These costs are omitted here since they can be expected to be small relative to the construction cost and operation costs of the disposal facility. Rothwell and Rust (1997) develop a dynamic programming model to empirically analyse the optimal operation, refuelling and closure decision of a nuclear power plant, when the plant may be in need of periodical costly maintenance (such as reactor part replacement). They assume fixed maximum operating periods (either 40 or 60 years), and show that the stochastic occurrence of costly maintenance operations have a significant effect on the possibility of an early closure. Hence they analyse a similar question as we do, namely when it is optimal to shut down the plant, but with a different driving force. Instead of stochastic costly maintenance, in our model the waste storage and disposal, an aspect omitted by Rothwell and Rust (1997), may affect the shutdown decision. In addition, our focus is on the socially optimal decisions contrary to Rothwell and Rust (1997).[9]

Other studies have focused on climate change and energy mix, bequest value of waste disposal and on the effect of waste shipments on property values. Chakravorty et al. (2012) investigate the role of nuclear power and uranium reserves in meeting the climate goals. They find that nuclear power can offer an inexpensive alternative for energy production in the coming decades, but after that the increasing uranium price and waste storage and disposal costs make nuclear power more expensive option compared to other energy sources unless reprocessing of the waste becomes available. Riddel and Shaw (2003) examine the bequest value in the context of final nuclear waste disposal at the Yucca Mountain in the U.S., and find that the current generation is willing to sacrifice for the future generation. Gawande et al. (2013) show that the nuclear waste shipments have a negative impact on the property values at the vicinity of the transport route.

In addition, the nuclear power generation and waste disposal problem has similarities with exhaustible resource production as such production leaves behind a pollution stock that needs reclamation (Lappi, 2018; Yang and Davis, 2018; Lappi, 2020). In Yang and Davis (2018), exhaustible resource production generates a pollution stock as a side-product, which must be reclaimed after the production has been shut down. There are of course multiple differences between the models, but perhaps the most central ones are the differences in production technology, and in that the nuclear waste stock causes negligent or zero damages. Another difference is that, by assumption, the pollution stock in Yang and Davis (2018) does not decay. The reclamation or clean-up model of Lappi (2018, 2020) allows for decay of the stock, and it is in fact used here as a starting point for modelling the nuclear waste storage and disposal. Lappi (2020) has stock decay in his model, but the focus is on mining.

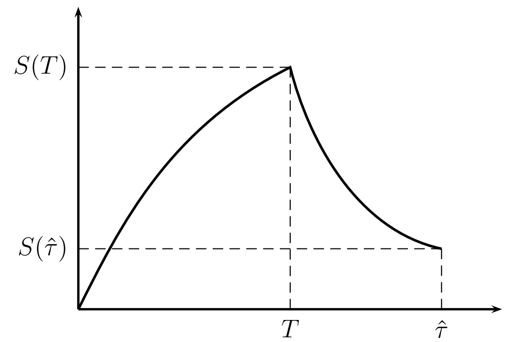

Fig. 1. The evolution of waste heat generation, when the plant is shut down at time T and the waste is disposed of at time $\hat{\tau}$.

3. Notation and assumptions

The nuclear power plant is run during the production stage $[0, T]$ at the end of which the plant is shut down at the optimal date T. Waste storage and disposal stage begins after the plant shutdown and this stage covers the interval $[T, \infty)$. During the production stage the plant operates at its maximal constant capacity using q units of fuel per unit of time.[10] Plant produces electricity at a constant marginal revenue p, which is assumed to be larger than the unit cost of uranium fuel w. The interest rate is denoted with r.

In addition to electricity, the plant produces spent nuclear fuel (nuclear waste) to be stored and disposed of. Storing and disposing the waste is costly and this cost depends on the mass and the heat generated by the waste. The heat generation is described using a model with multiple waste classes and it is presented in Appendix A.1. The heat generation has a different time evolution during the production stage compared to the period after shutdown. Namely, the total heat generation reads at any $t \in [0, T]$

$$S(t) = q \sum_{i=1}^{k} \frac{\alpha_i}{\delta_i}(1 - e^{-\delta_i t}), \tag{1}$$

where k is the number of different waste classes, α_i is the amount of new heat generation to class i which is produced per unit of fuel and δ_i is the decay rate of heat generation in class i. Let $\hat{\tau}$ be the date at which the waste is disposed of. After shutdown, that is, at any $t \in [T, \hat{\tau}]$, the total heat generation is given by

$$S(t) = \sum_{i=1}^{k} n_{i,T} e^{-\delta_i (t-T)}. \tag{2}$$

where $n_{i,T}$ is the heat generation in class i at the shutdown date. Therefore, the heat generation of the waste grows during the production stage and decreases during the waste storage and disposal stage. Note that S is strictly concave before the shutdown date and strictly convex after it. This is illustrated in Fig. 1.

The storage and disposal costs of nuclear waste depend on the waste mass in addition to heat generation. Mass M grows linearly with the

[9] Even though we analyse social optimum, there are no damages caused by the waste. This is due to the implicit assumption that the best available technology is applied, which effectively isolates the nuclear waste from the living world. This means that the waste does not cause "externality damages". The damages could in principle be caused by leaks or accidents, but these damages are not taken into account, and neither are the other social costs related for example people's risk perceptions (Huhtala and Remes, 2017).

[10] Refuelling and other possible cessations of production are not modelled.

used fuel according to equation $\dot{M}(t) = q$. Given zero amount of waste at the commission of the plant, the mass at time t is given by equation $M(t) = qt$. The waste mass at the shut down date T is $M(T) = qT$ and it stays fixed during the waste storage and disposal stage.

The cost of storing the waste in a wet or dry (interim) storage facility is given by a convex cost function W. The cost at time t is $W(S(t), M(t))$ with $W_S > 0$ and $W_M > 0$. This cost is borne as long as the waste is stored on the surface, but when the waste is disposed to the repository this cost becomes zero. The disposal cost at time t depends on total heat generation at time t and mass of the waste at the shutdown date, and this cost is denoted with $C(S(t), M(T))$, where the cost function C is convex with respect to S and satisfies inequality $C_S > 0$. This cost includes the cost related to the construction of the deep geological repository and the transportation and encapsulation costs. In principle this cost could be used to describe the share of the centralized storage facility cost, if the interest would be on the trade-offs between decentralized and centralized storage (Wealer et al., 2017), rather than between storage and disposal like here. In addition to these costs, the nuclear plant components must be maintained, repaired and possibly replaced as the plant ages. These repair or maintenance costs are assumed increasing in the age of the plant and captured by a convex function K with $K'(t) > 0$. Before moving on to analyse the model, it should be highlighted that any costs or damages due to fallout risk and accidents are not explicitly modelled.

4. Waste storage and disposal stage

The model is analysed backwards starting from the waste storage and disposal stage, which begins at the shutdown date T of the plant. The total heat generation and the waste mass at time T are inherited from the production stage, which is analysed in Section 5. The problem for the regulator is to minimize the total discounted waste storage and disposal costs by choosing the disposal date given heat decay and fixed waste mass. This problem is presented in Appendix A.2, and it can be rewritten as

$$\max_{\{\tau\in[0,\infty)\}} \left\{ -\int_0^\tau W(S(t;T), M(T))e^{-rt}\,\mathrm{d}t - C(S(\tau;T), M(T))e^{-r\tau} \right\}, \quad (3)$$

where $S(t;T) = \sum_{i=1}^{k} n_{i,T} e^{-\delta_i t}$ by Eq. (2) and τ is the disposal date (after shutdown). The model has a more specific pollution stock description than the one in the clean-up model of Lappi (2018). The first result about the optimal waiting rule is essentially the same as in his model, and in the current context it characterizes the choice of the optimal date to dispose the nuclear waste to a deep geological repository. It is possible that the problem in (3) has no solution. In this case the waste is stored in an on-ground facility forever. Although the focus here is on commercial waste, this rule can be also used to characterize the disposal decision of nuclear waste from past military programmes.

Proposition 1. *Suppose that the waste storage and disposal problem (3) has a solution $\tau^* \in (0,\infty)$. Then the optimal nuclear waste disposal date τ^* satisfies the following equation:*

$$W(S(\tau;T), M(T)) = rC(S(\tau;T), M(T)) - \left.\frac{\mathrm{d}}{\mathrm{d}t}\right|_{t=\tau} C(S(t;T), M(T)).$$

Proof. See Appendix A.3. □

This equation can be interpreted as follows. On the left-side is the cost of waiting with the nuclear waste disposal, which is the amount of interim waste storage costs that are borne during an additional waited time unit. On the right-side is the corresponding benefit of waiting, which describes the development of present value of the waste disposal cost. It has two parts. First, waiting one more unit of time means that the waste disposal cost is moved one unit of time to the future. This saved cost is valued at the interest rate. Second, waiting one more unit of time implies that the heat generation is decreased. Since the disposal cost is increasing in the heat generation of the waste, the disposal cost is decreased by waiting one time unit. In practice the heat generation is very high during the first years after the shutdown and decreases at a relatively fast pace. This means that the benefit of waiting also decreases and a time instant may be found at which the disposal cost has reached a low enough level to warrant disposal.

Next we find sufficient conditions for the uniqueness of the solution to the maximization problem.

Proposition 2. *Suppose that the number of waste classes is greater than one, $rC_{SS} - W_{SS} \geq 0$ and $C_{SSS} \geq 0$. Then the solution to waste storage and disposal problem in (3), if it exists, is unique.*

Proof. See Appendix A.4. □

This result states that the solution (if it exists) is unique given that there are more than one nuclear waste class, the interest rate is high enough ($r \geq W_{SS}/C_{SS}$) and the third derivative of the disposal cost function with respect to the heat generation is non-negative. These conditions for the partial derivatives need not hold in general, but note that they do hold for example when C is quadratic or linear and W is linear with respect to the heat generation. The optimal disposal date depends on many parameters, and it is denoted with $\tau^* = \tau(T)$. Hence the explicit dependency is shown only for the shutdown date. The dependency on the other parameters, such as the decay parameters, is left out from the notation.

The value function of the waste storage and disposal problem in (3) is defined as

$$V(T) := -\int_0^{\tau^*} W(S(t;T), M(T))e^{-rt}\,\mathrm{d}t - C(S(\tau^*;T), M(T))e^{-r\tau^*}. \quad (4)$$

It gives, after multiplying by -1, the amount of money needed to carry out the nuclear waste storage and disposal after the nuclear power plant has been shut down. Discounting this from the shutdown date T to the plant commission date $t = 0$ gives then the amount of money that must be deposited to a fund at the commission date to cover in full the storage and disposal of the spent nuclear waste (assuming that an interest is paid using rate r). Similarly to Lappi (2020), this sum also acts as the scrap value for the production stage problem to be analysed in the following section. At this point, we assume τ^* satisfies a sufficient condition for a strict local maximum presented in Appendix A.5. This additional assumption is made in order to analyse the properties of the scrap value function using an envelope theorem.

Proposition 3. *Suppose that the waste storage and disposal problem has a solution $\tau^* \in (0,\infty)$. Then $V_T(T) < 0$.*

Proof. See Appendix A.5. □

This result means that an extension of the production horizon of the power plant increases the amount of funds that must be deposited at the commission date of the plant. Moreover, inspection shows that an increase in T increases the amount of deposited funds irrespective when this deposit is done. Before moving onto the analysis of the production stage, note that if it is never optimal to dispose the waste, the value of this stage consists only of the discounted interim waste storage cost.

5. Production stage

The plant is operated at the maximal fixed capacity q and therefore the choice is only made on the plant's operation life-time T.[11]

[11] Licensed plant life-times vary a lot between plants and range from 30 to 50 years in Europe (European Commission, 2017). In the U.S., licences have been granted for 40 years, but almost all plants have received a 20 year extension for their licence (U.S. Government Accountability Office, 2012). Even longer life-times for the existing plants have been discussed.

Neglecting the decommissioning costs (or including them into the scrap value as a constant), the problem for the regulator is to maximize the discounted net profit given the build-up of waste heat generation and mass:

$$\max_{\{T\in[0,\infty)\}} \int_0^T \Big((p-w)q - W(S(t),M(t)) - K(t)\Big)e^{-rt}\,\mathrm{d}t + V(T)e^{-rT}, \tag{5}$$

where S is given by (1) and $M(t)=qt$. The following result characterizes the optimal shutdown date for the nuclear plant:

Proposition 4. *Suppose that the shutdown problem (5) has a solution $T^*>0$. Then the optimal shutdown date of the nuclear power plant satisfies the following equation:*

$$(p-w)q - rV(T) = W(S(T),M(T)) + K(T) - V_T(T).$$

Proof. See Appendix A.6. □

An interior optimal shutdown date for a nuclear power plant equalizes the benefit and cost of continuing electricity production in the plant. The benefit consists of the net revenue $(p-w)q$ and of the interest on the avoided waste storage and disposal stage value. The cost of continuing production is the sum of the additional interim waste storage cost, W, the repair cost, K, and the loss due to waste build-up induced decrease in the waste storage and disposal stage value, V_T. To compare this shutdown date to the case where the post-production waste storage and disposal decision is omitted, rewrite the rule as

$$(p-w)q - W(S(T),M(T)) - K(T) = rV(T) - V_T(T), \tag{6}$$

where the right-side describes the development of the present value of the waste management payment $-V$.[12] When the waste storage and disposal decision is omitted, the optimal shutdown date for the plant equalizes the left-side of (6) with zero. If the present value of the waste management payment is decreasing at the shutdown date, i.e., $rV(T)-V_T(T)<0$, the production stage is longer than when neglecting the waste storage and disposal costs. If the opposite holds, the production stage is shorter.

6. Optimal payment and regulation

In principle, there are multiple ways, such as trust funds or letter of credits, in which the resources to cover future waste management costs can be collected. Our main focus here is on the amount of money needed for management, and we only consider some specific forms of schemes such as direct payments by the operator. The amount of money the nuclear power firm must deposit to the nuclear waste fund by the shutdown date is the total waste storage and disposal cost, which has been discounted to the optimal shutdown date T^*. This amount is directly given by the value of storage and disposal stage $-V(T^*)$, and it depends on many parameters of the model including interest rate, capacity of the plant and net unit revenue. Possibly the most interesting relationship is between the payment and the interest rate. Note that the value of V depends on the interest rate r directly (see Eq. (4)), but this is not shown in the notation to avoid clutter. To investigate the relationship between the payment and the interest rate, the payment function is denoted with P and defined as

$$P(r) := -V(T(r)), \tag{7}$$

where $T(r) := T^*$ is the optimal shutdown date of the plant. It is assumed that the second derivative of the objective function (5) with respect to T is strictly negative at $T=T^*$.

[12] The reason why the comparison is possible is that the left-side of (6) is strictly decreasing in T.

Proposition 5. *If $\mathrm{d}/\mathrm{d}r(rV(T^*)-V_T(T^*))>0$, then $T_r(r)<0$, and if $\mathrm{d}/\mathrm{d}r(rV(T^*)-V_T(T^*))<0$, then $T_r(r)>0$. The sign of $P'(r)$ is given by the sign of $-V_T(T(r))T_r(r)-V_r(T(r))$, and is generally ambiguous.*

Proof. See Appendix A.7. □

The effect of waste management on optimal plant shutdown date is captured by the term $rV(T^*)-V_T(T^*)$, which is the net cost of continuing electricity production (evaluated at the optimal shutdown date) that is due to post-production waste management costs. Note that $\mathrm{d}/\mathrm{d}r(rV(T^*)-V_T(T^*)) = V(T^*)+rV_r(T^*)-V_{Tr}(T^*)$, where the first and the third term are strictly negative and the second is strictly positive. The proposition implies that if the net cost increases as the interest rate increases, the optimal shutdown date decreases. If the cost decreases, then the shutdown is delayed. As the plant shutdown may be brought forward or delayed as a result of an increase in the interest rate, the effect of interest rate on the optimal payment P is ambiguous. However, if the net cost of continuing production increases due to an increase in the interest rate (implying that $T_r<0$), the payment decreases as both the direct effect of the interest rate on the payment, namely $-V_r$, and the indirect effect, $-V_T T_r$, are strictly negative. The other case, where the payment increases due to an increase in the interest rate requires that the increase in the interest rate causes a relatively large increase in the shutdown date of the plant.

For any interest rate, the amount of money required for the socially optimal waste storage and disposal is given by P in Eq. (7). Hence the regulator must collect this amount from the firm or receive other sufficient guarantees. In addition, the regulation must give the firm incentives to shutdown the plant at the socially optimal shutdown date T^*. To guarantee in the above sense the proper operation of the plant and management of the waste, the regulator has multiple regulatory options, which are discussed below.

Regulation 1: The first option is to simply set the optimal shutdown date that the firm must respect to T^* and a lump-sum payment $-V(T^*)e^{-rT^*}$ to be paid when the plant begins its operation. Of course, if there is no risk of insolvency, the firm can be required to pay amount $-V(T^*)e^{-r(T^*-t)}$ at some date t after the commission of the plant. Both of these work, but their drawbacks are clear: Full payment at the commission date requires possibly a lot of funds from the firm upfront, but delayed payment comes with the risk of bankruptcy.

Regulation 2: The second option is to set a tax that depends on the shutdown date chosen by the nuclear firm, say $\Lambda(T)$. The firm's problem is to

$$\max_{\{T\in[0,\infty)\}} \int_0^T \Big((p-w)q - W(S(t),M(t)) - K(t)\Big)e^{-rt}\,\mathrm{d}t - \Lambda(T)e^{-rT}, \tag{8}$$

where S solves (1) and $M(t)=qt$. Therefore setting $\Lambda(T)=-V(T)$ makes the firm solve the regulator's problem and the firm chooses the optimal shutdown date T^*.[13] The tax is paid at the shutdown date, which might be a problem if the firm is at a risk of insolvency.

Regulation 3: The third option for regulation is to require the firm to pay (any) fraction of its profits at any time instant into a nuclear waste fund with the requirement that the fund's monies will be used to finance the waste storage and disposal after the plant has been shut down. This means that the regulator announces at the commission date of the plant that the amount of funds at the shutdown date T, which is chosen by the firm, must equal $-V(T)$. Firm's incentives can be analysed using the following problem:

$$\max_{\{\theta(t)\in[0,1],T\in[0,\infty)\}} \int_0^T \Big((p-w)q - W(S(t),M(t)) - K(t)\Big)(1-\theta(t))e^{-rt}\,\mathrm{d}t \tag{9}$$

[13] Similar regulation is analysed in many contexts, for example by Loeb and Magat (1979), Kim and Chang (1993) and Yang and Davis (2018).

$$\text{s.t}\quad \dot{B}(t) = rB(t) + \theta(t)\big((p-w)q - W(S(t), M(t)) - K(t)\big), \tag{10}$$

$$B(0) = 0, \quad B(T) = -V(T), \tag{11}$$

where $B(t)$ denotes the amount of money in the fund at time t, and, again, S solves (1) and $M = qt$. The objective here is to first show that for a firm that obtains strictly positive discounted profit and meets the constraint set by the regulator, any payment function is optimal and that the optimal shutdown date equals the socially optimal shutdown date T^*. Second objective is to present a formula for a constant payment scheme, since in practice the nuclear waste fee is often a constant.[14]

Proposition 6. *If the firm makes a strictly positive profit, then the plant is shut down at the socially optimal date with any payment function that collects sufficient amount of money for waste management. A constant fee to the nuclear waste fund is given by*

$$\theta = \frac{-V(T^*)e^{-rT^*}}{\int_0^{T^*}\big((p-w)q - W(S(z), M(z)) - K(z)\big)e^{-rz}\,\mathrm{d}z}.$$

Proof. See Appendix A.8. □

Hence the constant fee equals the ratio between the discounted waste management payment and the total discounted profit from the plant. This constant belongs to $(0,1)$ since the objective function of the regulator obtains a strictly positive value at the optimal shutdown date (otherwise there would be no reason to commission the plant). In the above the fee is paid as a fraction of the profit, but other types of fees are used in practice. For example, in the U.S. and Sweden the fee is based on the produced electricity. The fee was in the U.S. 0.1 cents per produced kWh. A fee based on the produced electricity is given by

$$\theta = \frac{-V(T^*)e^{-rT^*}}{q(1-e^{-rT^*})/r} \in (0,1), \tag{12}$$

which is obtained by similar arguments as the result in the previous proposition and by integration (note that the amount of money transferred to the account at any time instant is θq). Irrespective of the form of the fee used, the fee varies across plants if the plants are heterogeneous with respect to marginal revenue, capacity, fuel price, repair costs or waste management costs. This is contrary to the practice of collecting the same fee from all the firms (or plants).

7. Application

The model is illustrated by a numerical application, which is based on the available data on an Olkiluoto 3-type plant (EPR).

Data and calibration. Table 1 presents the data on the plant specifications, fuel costs and prices. Prices and unit costs are assumed to remain constant during the plant's operation life. Annual fuel use is given by equation $q = Y/\eta\beta$ and the data on Table 1 gives as the fuel use approximately 32.5 tU/year. The annual net revenue from electricity generation is constant $[(p - c_{OM})\eta\beta \cdot 24 \cdot 1000 - w]q = 390$ million euros.

The disposal cost function and the interim waste storage cost function are assumed to have the following forms:

$$C(S, M) = c_0 + c_1\frac{S}{M} + c_2 M, \quad \text{and} \quad W(M) = w_0 + w_1 M. \tag{13}$$

The interim waste storage cost, $W(M)$, is assumed to be independent of waste heat generation, S. Data exists to fix plausible values for the parameters c_2 and w_1, but there is only partial data available for the other parameters. For this reason parameters c_0 and w_0 are calibrated for an assumed parameter value c_1. The operator of Olkiluoto 3 plant has estimated that the plant will be operational for at least 60 years (Teollisuuden Voima, 2010), and this date is used in the calibration exercise. When Olkiluoto 3 reactor becomes active, Finland will have five operational commercial reactors, and the waste from these reactors will be disposed in a single repository. The cost of this repository including encapsulation facility has been estimated to be around 3 500 million euros (Ministry of Employment and the Economy (Finland), 2015; Posiva, 2016), and the waste share of Olkiluoto 3 plant is 37 percent.[15] The interim waste storage cost for a plant that generates 2030 tonnes of waste is approximately 14.15 mEUR/year (Nuclear Energy Agency, 2013). The disposal cost is calibrated for a situation where most important heat generation has diluted away. Therefore, 100 years is used for the calibration disposal date. With a description of the decay heat evolution after plant shutdown (presented below), one knows the decay heat generation at the disposal date. This is given for the used five decay class case by $S_{cal} = \sum_{i=1}^{5} n_{i,60}e^{-100\delta_i}$ with $n_{i,60} = \alpha_i q\big(1 - e^{-60\delta_i}\big)/\delta_i$. The waste mass is $M_{cal} = 60q$. Hence, using the functional forms in (13), the parameters c_0 and w_0 obtain values

$$c_0 = 0.37 \cdot 3500 - c_1\frac{S_{cal}}{M_{cal}} - c_2 M_{cal}, \quad \text{and} \quad w_0 = 14.15 - w_1 M_{cal}. \tag{14}$$

Table 2 presents the necessary storage, disposal and repair cost parameters. The repair cost function form is assumed to be given by $K(t) = \max\{0, k_1 + k_2(t - k_3)\}$. This form and the parameter values from Table 2 imply that the plant operator must pay for repairs for some time before and after the life-time of the plant (60 years) used in the calibration of the waste storage and disposal functions.[16]

Waste decay and production parameters for the waste classes (δ_i and α_i) are estimated using the heat generation data of an EPR-type plant available in Anttila (2005). The decay heat generation was estimated

Table 1
Plant and fuel specifications and prices.

Parameter	Value and unit	Description
p	40 EUR/MWh	Electricity price[a]
β	45 GWd/tU	Fuel burnup[b]
η	0.37	Thermal efficiency[b]
Y	13 TWh	Annual electricity production[b]
c_{OM}	11.57 EUR/MWh	Unit O&M cost[c]
w	1.25 mEUR/tU	Unit fuel cost[d]

[a]Nord Pool electricity price.
[b]Source: Teollisuuden Voima (2010).
[c]Source: International Energy Agency (2015).
[d]Source: World Nuclear Association (2019).

Table 2
Waste storage (interim storage), disposal and repair costs.

Parameter	Value and unit	Description
w_1	653 EUR/tU	Marginal interim storage cost[a]
c_r	3500 mEUR	Disposal facility cost[b]
c_1	0.1 mEURtU/W	Disposal cost parameter (heat)[c]
c_2	0.112 mEUR/tU	Disposal cost parameter (mass)[a]
k_1	320 mEUR	Repair cost parameter[c]
k_2	5 mEUR/year	Repair cost parameter[c]
k_3	60 years	Repair cost parameter[c]

[a]Source: Nuclear Energy Agency (2013).
[b]Source: Posiva (2016).
[c]Source: Assumed.

[14] Lappi (2020) contains a similar result except for the constant fee formula in a mining context, but there the regulator sets directly the terminal date at the socially optimal level. Here the date is a choice variable for the firm.

[15] Posiva (2016) has estimated that Olkiluoto 3 produces 2030 tU over its estimated 60 year plant life-time, and therefore the waste share of Olkiluoto 3 is $2030/(950 + 2500 + 2030) \approx 0.37$ (Posiva, 2016).

[16] In addition, the decommission cost of the plant are assumed to be one fifth of the total decommission cost of all Finnish plants. The total cost is 1000 million euros (Ministry of Employment and the Economy (Finland), 2015), so the Olkiluoto 3 plant's share is 200 million euros. This is paid when the plant is shutdown.

Table 3
Waste decay and production parameters.
Source: Own estimations.

Parameter	Value (1/year)	Parameter	Value (W/tU)
δ_1	4.0	α_1	42000
δ_2	$5.7 \cdot 10^{-1}$	α_2	19000
δ_3	$2.3 \cdot 10^{-2}$	α_3	2400
δ_4	$2.1 \cdot 10^{-3}$	α_4	340
δ_5	$7.5 \cdot 10^{-5}$	α_5	40

from data covering 0.11 years to 10 000 years. The details of estimation are presented in Appendix A.9. Five decay modes was deemed sufficient representation of the heat generation process. The results of these estimations are presented in Table 3. The two decay modes with highest heat generation decay rapidly as their decay timescales are 0.25 and 1.75 years. The third decay mode with 40 year decay timescale is the most relevant in the context of the study. Two last decay modes represent relatively small share of decay heat generation and remain relatively stable in the time frame of interest.

With the data in the tables, the calibrated cost parameters equal approximately $c_0 = 1030$ and $w_0 = 12.9$. Fig. 2 shows the evolution of the heat generation, heat–mass ratio and the waste management costs in the calibration case. Note that the interim storage cost W is fixed after plant shutdown.

Solution method. The quantitative model is solved using a discrete time approximation with annual time periods. The model is solved in two steps. In the first step, the optimal disposal time is solved for all feasible production horizons. In the second step, the production horizon is optimized given the optimal solutions for the disposal problems. The compact structure of the problem allowed calculation of all possible production horizon and disposal time combinations. The optimum was chosen by a simple search algorithm.

In addition to the first-best solution, we solved a problem where the firm has a higher discount rate than the regulator. The regulator uses its low discount rate to determine optimal disposal time. The firm is obligated to use this disposal time, which is non-optimal from its point of view. The regulator's problem is solved like the first-best problem and it determines a *regulated disposal time*. The firm's problem needs modification. In the first step, instead of optimizing the disposal time, the value of waste is calculated for all feasible production horizons using the regulated disposal time. In the second step, the production horizon is optimized using the value of waste with the regulated disposal time.

Results. Given the quality of the available data and uncertainties surrounding the key parameters related to waste management costs, the following numerical results should be taken as illustrative only. In short, the main result is that disposal of nuclear waste into a deep geological repository is optimal only with a low interest rate of around one percent. This means that from the cost minimization point of view it is cheaper to keep the waste in a ''interim'' storage facility indefinitely instead of constructing an expensive final disposal facility. For a one percent interest rate the plant is run for 61 years (see the first row of Table 4). This is followed by an interim storage period after which the waste is disposed of 51 years after shutdown. The present value of the profit from the plant including the waste management costs is around 6230 million euros, which is far less than the cost estimate for the construction of the Olkiluoto 3 plant (around 8500 million euros). The discounted waste management payment is around 742 million euros, when the regulator's discount rate is applied. However, if a larger interest is paid, say five percent, the payment is only 65 million euros.

Table 4 shows the sensitivity of the model output with respect to interest rate, disposal cost parameters c_0 and c_1, and price of electricity.

The first two rows of Table 4 show that as the interest rate is increased from one percent to three or five (or just to two percent), the cost-minimizing solution is to store the waste in the ''interim'' storage facility indefinitely instead of disposing it at some date. Increasing the interest rate has a small effect on the shutdown date, but has a large effect on the discounted profit from the plant. The discounted waste management payment drops significantly as the interest rate is increased.[17]

Varying the disposal cost parameters c_0 and c_1 has no significant effect on the shutdown date of the plant, discounted profit or the discounted waste management payment. However, decreasing the value of c_0 by ten percent, and thus decreasing the benefit of waiting, brings the disposal date significantly forward from 51 to 26 years after shutdown. Increasing the parameter value by ten percent has the opposite effect. Similarly, decreasing the value of parameter c_1 decreases the disposal date, and an increase in c_1 results in an increase in the disposal date (see also Fig. 3).

As expected, the price of electricity has a significant effect on the profitability of the plant. A ten euro decrease in the price decreases the shutdown date and results in a relative small discounted profit, but an increase of the same size leads to significant extension in the plant's production horizon and more than doubles the discounted profit. Even though the high electricity price increases the shutdown date and more waste is produced, the discounted waste management payment decreases due to discounting.

In the above first-best solution with one percent interest rate, it is optimal to dispose the waste 51 years after plant shutdown.[18] However, the firm might have higher interest rate than this, say five percent. In that case it would not be optimal from the firm's point of view to dispose the waste at all and the plant would be shut down at year 63 (see the second row of Table 4). What is the effect of designing the disposal date with one percent interest rate on the shutdown date chosen by the firm and on the present value waste management payment when the firm uses five percent rate? Our numerical model shows that the regulation leads the firm to shutdown the plant at year 64, that is, one year after the shutdown date with the regulation that is designed using the firm's interest rate. In addition, the present value waste management payment is 2.9 million euros larger.

8. Conclusions, caveats and possible further research

This paper analyses the socially optimal nuclear power production and waste management using a two-stage model, where the operation duration for a constant capacity nuclear power plant is decided together with the date to conduct the final disposal of the nuclear waste into a deep geological repository. The study emphasizes that postponing the disposal may decrease the overall waste management costs as the delay in disposal decreases the costs as radioactivity or heat generation of the waste decays. In addition, the numerical illustration shows that the policy that advocates disposal in a deep geological repository may be misguided from cost perspective as on ground storage in perpetuity is cheaper at least for interest rates higher than one percent. In any case, the waste management fee must be designed separately for every individual plant as the plants are not identical in their capacities, prices and reactor designs.

However, the model is based on multiple simplifications. First, the disposal of the nuclear waste produced by the plant is assumed to occur instantaneously at the chosen disposal date. In reality, however, the process of disposing the waste is an ongoing gradual process after the deep geological repository has been built. The simplification makes the trade-offs related to timing clear, but may imply imprecise waste management costs. Therefore replacing this assumption with a continuous

[17] The presented payment numbers are obtained by fixing the last possible date to dispose the waste at 500 years, which means that the numbers are only slightly off from the true ones, where only the interim storage cost is paid indefinitely.

[18] Given the base case parameter values reported below Table 4.

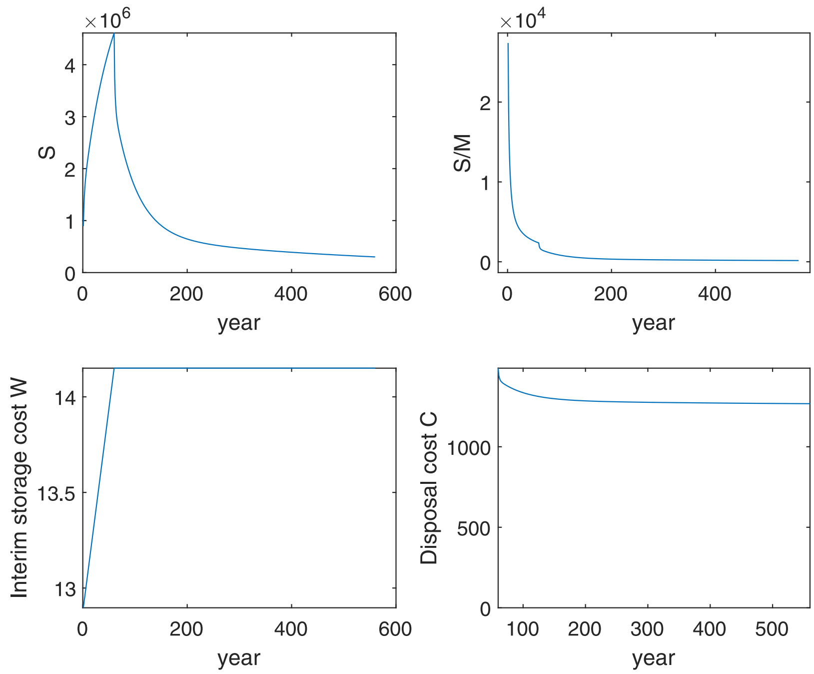

Fig. 2. Evolution of the waste heat generation, heat–mass ratio, interim storage cost and the disposal cost, when the plant is shutdown after 60 years of operation.

Table 4
Sensitivity of the solution with respect to key parameter values.

Parameter value	T	τ	Discounted profit	$-V(T)e^{-rT}$	$-V(T)e^{-0.05T}$
Base case	61	51	6230	742	65
$r = 0.03$	62	∞	4980	75	22
$r = 0.05$	63	∞	3850	12	12
$c_0 = 930$	61	26	6270	703	61
$c_0 = 1140$	61	113	6200	769	67
$c_1 = 0.05$	61	22	6240	734	64
$c_1 = 0.15$	61	67	6230	745	65
$p = 30$	35	50	1320	912	225
$p = 50$	87	56	12980	603	19

Parameter values are varied one-by-one relative to the base case with $r = 0.01$, $c_0 = 1030$, $c_1 = 0.1$ and $p = 40$. The unit of the discounted profit and the discounted waste management payment is million euros.

waste disposal process may yield more precise quantitative information for policy.

Second, accident and fallout risk during waste management operation was not explicitly modelled. These risks can be expected to be different between on-ground storage and geological disposal. A quantification, although a difficult task, might yield relevant insights on optimal waste management and disposal timing.

Third, our planning solution approach omits the interaction between private plant operator and public authorities. For example, in a model with accident and fallout risks, the question of liabilities could be important. This might provide a line for future studies. Our model did not include explicit taxes. Yet, a decentralization of the planning model, should also consider corporate taxation. The present model implies a constant tax rate on profits but a more complicated tax structure could have an impact on quantitative results. This is left for future studies.

Fourth, a relevant aspect of the current policy discussions is the possibility of extending the life-times of the plants in the existing nuclear fleet. These extensions come with interesting trade-offs because extensions would postpone the decommission, but also produce more waste. An investigation of this, combined possibly with price and cost uncertainty, might be an option for future research. Relatedly, the plant operator may become insolvent during its operation with possible adverse effects, for example, to tax payers. This means that an investigation of firm's liability and also the means for collecting the money for waste management are possible topics for future research.

Finally, the model and the related options for regulation presented in Section 6 assume complete information. Implementation of some of the options, where the payment is partly based on the socially optimal shutdown date, need information on the parameters related to plant operation including prices and maintenance costs. But to implement some of the options the regulator needs only to know the waste storage and disposal costs in order to form the waste storage and disposal payment that depends on the shutdown date chosen by the firm. In practice this information, in particular the disposal cost, is difficult to obtain, and it may be private information for the firm. Hence a possibility for future research is to investigate the optimal mechanism that can be used to formulate the (second-best) payment. This might mean that the tax payers must bear some of the waste storage and disposal costs.

CRediT authorship contribution statement

Pauli Lappi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Jussi Lintunen:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization.

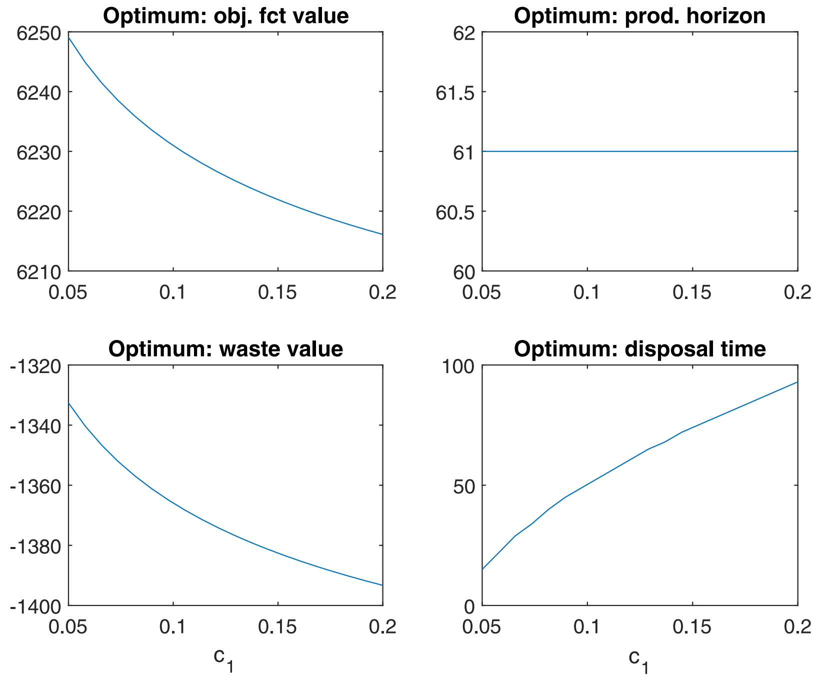

Fig. 3. Sensitivity of the solution with respect to disposal cost parameter c_1 that multiplies heat–mass ratio (with $r = 0.01$, $c_0 = 1030$ and $p = 40$). Objective function value is the discounted profit from the plant and the waste value is the optimal waste management cost at the shutdown date.

Appendix

A.1. A model for heat generation

To model the heat generation of the waste, the waste is divided into k classes according to the speed at which the heat generation diminishes. The size of class $i = 1, \ldots, k$ at time t, $N_i(t)$, describes the decay heat generation of that waste class, and the time evolution of these classes depends on whether the plant has been shut down or not. When the plant is operational the classes evolve according to equations

$$\dot{N}_i(t) = \alpha_i q - \delta_i N_i(t), \tag{A.1}$$

where α_i describes the amount of new heat generation to class i which is produced per unit of fuel and δ_i is the decay rate of heat generation. The heat generation is zero at the commission date of the plant. As electricity is produced the heat generation grows according to (A.1). The heat generation in class i at the shutdown date is denoted with $n_{i,T} := N_i(T)$. After the plant has been shut down no new waste is produced and therefore equations

$$\dot{N}_i(t) = -\delta_i N_i(t) \tag{A.2}$$

describe the evolution of the heat generation classes until the time the waste is disposed of. Solving equations in (A.1) and (A.2) gives the following formulas for the heat generation in any of the classes:

$$N_i(t) = \frac{\alpha_i q}{\delta_i}\left(1 - e^{-\delta_i t}\right) \quad \text{for} \quad t \in [0, T], \tag{A.3}$$

and

$$N_i(t) = n_{i,T} e^{-\delta_i (t-T)} \quad \text{for} \quad t \in [T, \hat{\tau}], \tag{A.4}$$

where $\hat{\tau}$ is the date at which the waste is disposed of. Note that $n_{i,T} = \alpha_i q\left(1 - e^{-\delta_i T}\right)/\delta_i$. Hence the evolution of these classes is determined by the choice of the shutdown date T and the disposal date $\hat{\tau}$. The total heat generation at any time instant $t \in [0, \infty)$ is

$$S(t) = \sum_{i=1}^{k} N_i(t), \tag{A.5}$$

Note that $S(0) = 0$ and $S(T) = \sum_{i=1}^{k} n_{i,T}$. Eqs. (1) and (2) given in the text follow from the above equations.

A.2. Waste storage and disposal stage problem

The problem is to

$$\max_{\{\hat{\tau} \in [T, \infty)\}} \left\{ -\int_T^{\hat{\tau}} W(S(z-T;T), M(T)) e^{-r(z-T)}\, \mathrm{d}z - C\left(S(\hat{\tau}-T;T), M(T)\right) e^{-r(\hat{\tau}-T)} \right\}, \tag{A.6}$$

where we abused the notation with

$$S(z-T;T) = \sum_{i=1}^{k} n_{i,T} e^{-\delta_i (z-T)} \quad \text{and} \quad S(0;T) = \sum_{i=1}^{k} n_{i,T}. \tag{A.7}$$

An introduction of the change of variables $t = z - T$ with $\tau := \hat{\tau} - T$ transforms this problem into problem in (3).

A.3. Proof of Proposition 1

The proof follows Lappi (2018) and is straightforward. A solution to the maximization problem (3) is a stationary point of the Lagrangian L, which is defined with equation

$$L(\tau) = -\int_0^{\tau} W(S(t;T), M(T)) e^{-rt}\, \mathrm{d}t - C\left(S(\tau;T), M(T)\right) e^{-r\tau} + \lambda \tau. \tag{A.8}$$

But since it is assumed that $\tau^* \in (0, \infty)$, multiplier λ equals zero, and the required formula follows from the definition of L by direct calculation and inspection using equation $L_\tau = 0$, or equivalently, equation

$$-W(S(\tau;T), M(T)) + rC(S(\tau;T), M(T)) - C_S(S(\tau;T), M(T))\dot{S}(\tau;T) = 0. \tag{A.9}$$

A.4. Proof of Proposition 2

Denote the heat generation of the waste at time t with $S(t)$. The time-derivative of S reads

$$\dot{S}(t) = -\sum_{i=1}^{k} \delta_i n_{i,T} e^{-\delta_i t}. \tag{A.10}$$

Lemma 1. *If $k = 1$, then*

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\dot{S}(\tau)/\ddot{S}(\tau)\right) = 0,$$

and, if $k > 1$, then

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\dot{S}(\tau)/\ddot{S}(\tau)\right) < 0.$$

Proof. The quotient is a constant $-1/\delta_1$, if $k = 1$. Case with $k > 1$: The derivative is

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\dot{S}(\tau)/\ddot{S}(\tau)\right) = \frac{\ddot{S}(\tau)^2 - \dot{S}(\tau)\dddot{S}(\tau)}{\ddot{S}(\tau)^2}. \tag{A.11}$$

The sign of this derivative is determined by the sign of the difference $\ddot{S}(\tau)^2 - \dot{S}(\tau)\dddot{S}(\tau)$. Note that

$$\ddot{S}(\tau)^2 = \left(\sum_{i=1}^{k} \delta_i^2 n_{i,T} e^{-\delta_i \tau}\right)^2 \tag{A.12}$$

$$= \delta_1^2 n_{1,T} e^{-\delta_1 \tau}\left(\delta_1^2 n_{1,T} e^{-\delta_1 \tau} + \cdots + \delta_k^2 n_{k,T} e^{-\delta_k \tau}\right) + \cdots$$
$$+ \delta_k^2 n_{k,T} e^{-\delta_k \tau}\left(\delta_1^2 n_{1,T} e^{-\delta_1 \tau} + \cdots + \delta_k^2 n_{k,T} e^{-\delta_k \tau}\right), \tag{A.13}$$

and that

$$\dot{S}(\tau)\dddot{S}(\tau) = \left(\sum_{i=1}^{k} \delta_i n_{i,T} e^{-\delta_i \tau}\right)\left(\sum_{i=1}^{k} \delta_i^3 n_{i,T} e^{-\delta_i \tau}\right) \tag{A.14}$$

$$= \delta_1 n_{1,T} e^{-\delta_1 \tau}\left(\delta_1^3 n_{1,T} e^{-\delta_1 \tau} + \cdots + \delta_k^3 n_{k,T} e^{-\delta_k \tau}\right) + \cdots$$
$$+ \delta_k n_{k,T} e^{-\delta_k \tau}\left(\delta_1^3 n_{1,T} e^{-\delta_1 \tau} + \cdots + \delta_k^3 n_{k,T} e^{-\delta_k \tau}\right). \tag{A.15}$$

Therefore all the terms of type $\delta_i^4 n_{i,T}^2 e^{-2\delta_i \tau}$ are eliminated from the difference $\ddot{S}(\tau)^2 - \dot{S}(\tau)\dddot{S}(\tau)$. Terms of the following type are left:

$$2\delta_i^2 n_{i,T} e^{-\delta_i \tau}\delta_j^2 n_{j,T} e^{-\delta_j \tau} - \delta_i n_{i,T} e^{-\delta_i \tau}\delta_j^3 n_{j,T} e^{-\delta_j \tau} - \delta_i^3 n_{i,T} e^{-\delta_i \tau}\delta_j n_{j,T} e^{-\delta_j \tau}, \tag{A.16}$$

where $i \neq j$. This equals

$$n_{i,T} n_{j,T} e^{-\delta_i \tau} e^{-\delta_j \tau}\left(2\delta_i^2\delta_j^2 - \delta_i\delta_j^3 - \delta_i^3\delta_j\right) = \tag{A.17}$$

$$n_{i,T} n_{j,T} e^{-\delta_i \tau} e^{-\delta_j \tau}\delta_i\delta_j\left(2\delta_i\delta_j - \delta_j^2 - \delta_i^2\right) = \tag{A.18}$$

$$- n_{i,T} n_{j,T} e^{-\delta_i \tau} e^{-\delta_j \tau}\delta_i^2\delta_j^2\left(\delta_i - \delta_j\right)^2 < 0. \tag{A.19}$$

Therefore $\ddot{S}(\tau)^2 - \dot{S}(\tau)\dddot{S}(\tau) < 0$ for all $k > 1$. The claim follows. □

Proof of Proposition 2. Suppose that the problem has two solutions denoted with τ_1 and τ_2, and let $\tau_1 < \tau_2$. Then there exists a local minimum between these maximums. Denote it with $\tau_{\min}$. The second derivative of the objective function evaluated at any of these dates can be written using Eq. (A.9) as

$$\left(-W_S(S(\tau), M(T)) + rC_S(S(\tau), M(T)) - C_{SS}(S(\tau), M(T))\dot{S}(\tau)\right)\dot{S}(\tau)$$
$$- C_S(S(\tau), M(T))\ddot{S}(\tau), \tag{A.20}$$

and it is non-positive at the maximum points (τ_1 and τ_2) and non-negative at the minimum point ($\tau_{\min}$). Since $\dot{S}(\tau) < 0$,

$$\left(-W_S(S(\tau), M(T)) + rC_S(S(\tau), M(T)) - C_{SS}(S(\tau), M(T))\dot{S}(\tau)\right)$$
$$- \frac{C_S(S(\tau), M(T))}{\dot{S}(\tau)/\ddot{S}(\tau)} \geq 0 \tag{A.21}$$

at $\tau = \tau_1$ and at $\tau = \tau_2$, and

$$\left(-W_S(S(\tau), M(T)) + rC_S(S(\tau), M(T)) - C_{SS}(S(\tau), M(T))\dot{S}(\tau)\right)$$
$$- \frac{C_S(S(\tau), M(T))}{\dot{S}(\tau)/\ddot{S}(\tau)} \leq 0 \tag{A.22}$$

at $\tau = \tau_{\min}$. Use the left-sides of these inequalities to define function f from $[0, \infty)$ to $\mathbb{R}$ with

$$f(\tau) = \left(-W_S(S(\tau), M(T)) + rC_S(S(\tau), M(T)) - C_{SS}(S(\tau), M(T))\dot{S}(\tau)\right)$$
$$- \frac{C_S(S(\tau), M(T))}{\dot{S}(\tau)/\ddot{S}(\tau)}. \tag{A.23}$$

Note that the function

$$\tau \mapsto \frac{C_S(S(\tau), M(T))}{\dot{S}(\tau)/\ddot{S}(\tau)} \tag{A.24}$$

is strictly increasing, because its derivative is

$$\frac{C_{SS}(S(\tau), M(T))\dot{S}(\tau)\cdot\dot{S}(\tau)/\ddot{S}(\tau) - C_S(S(\tau), M(T))\cdot(\mathrm{d}/\mathrm{d}\tau)\left(\dot{S}(\tau)/\ddot{S}(\tau)\right)}{\left(\dot{S}(\tau)/\ddot{S}(\tau)\right)^2} > 0 \tag{A.25}$$

by Lemma 1. Furthermore, the derivative of function

$$\tau \mapsto \left(-W_S(S(\tau), M(T)) + rC_S(S(\tau), M(T)) - C_{SS}(S(\tau), M(T))\dot{S}(\tau)\right) \tag{A.26}$$

can be written as

$$\dot{S}(\tau)\left(rC_{SS}(S(\tau), M(T)) - W_{SS}(S(\tau), M(T))\right)$$
$$- C_{SSS}(S(\tau), M(T))\dot{S}(\tau)^2 - C_{SS}(S(\tau), M(T))\ddot{S}(\tau), \tag{A.27}$$

which is non-positive by the function form assumptions. This means that function f is strictly decreasing, and therefore $f(\tau_1) > f(\tau_{\min}) > f(\tau_2)$. These inequalities contradict (A.21) and (A.22).

A.5. Proof of Proposition 3

The choice set of problem in (3) is not compact and the objective function is not (necessarily) concave. Therefore the envelope theorems in Milgrom and Segal (2002) cannot be applied. Recall the assumption that τ^* satisfies the following sufficient condition for a strict local maximum:

$$\left(-W_S(S(\tau), M(T)) + rC_S(S(\tau), M(T)) - C_{SS}(S(\tau), M(T))\dot{S}(\tau)\right)\dot{S}(\tau)$$
$$- C_S(S(\tau), M(T))\ddot{S}(\tau) < 0 \tag{A.28}$$

at $\tau = \tau^*$. Given the above assumption, an envelope theorem presented in Carter (2001, Corollary 6.1.1) can be applied. By the envelope theorem, the partial derivative of the value function V given in (4) with respect to the variable T evaluated at T equals the partial derivative of the objective function given in (3) with respect to T evaluated at T and at τ^*. Therefore

$$V_T(T) = -\int_0^{\tau^*}\left[W_S(S(t;T), M(T))S_T(t;T) + W_M(S(t;T), M(T))q\right]e^{-rt}\,\mathrm{d}t$$
$$- \left[C_S(S(\tau^*;T), M(T))S_T(\tau^*;T) + C_M(S(\tau^*;T), M(T))q\right]e^{-r\tau^*}. \tag{A.29}$$

Recall that $S(t;T) = \sum_{i=1}^{k} n_{i,T} e^{-\delta_i t}$ and $n_{i,T} = \alpha_i q\left(1 - e^{-\delta_i T}\right)/\delta_i$. Therefore

$$S_T(t;T) = q\sum_{i=1}^{k}\alpha_i e^{-\delta_i T} e^{-\delta_i t} > 0. \tag{A.30}$$

Furthermore, since $W_S > 0$, $C_S > 0$, $W_M > 0$ and $C_M > 0$ everywhere, $V_T(T) < 0$.

A.6. Proof of Proposition 4

The proof is similar to the proof of Proposition 1 presented in Appendix A.3. Proceeding as there gives equation

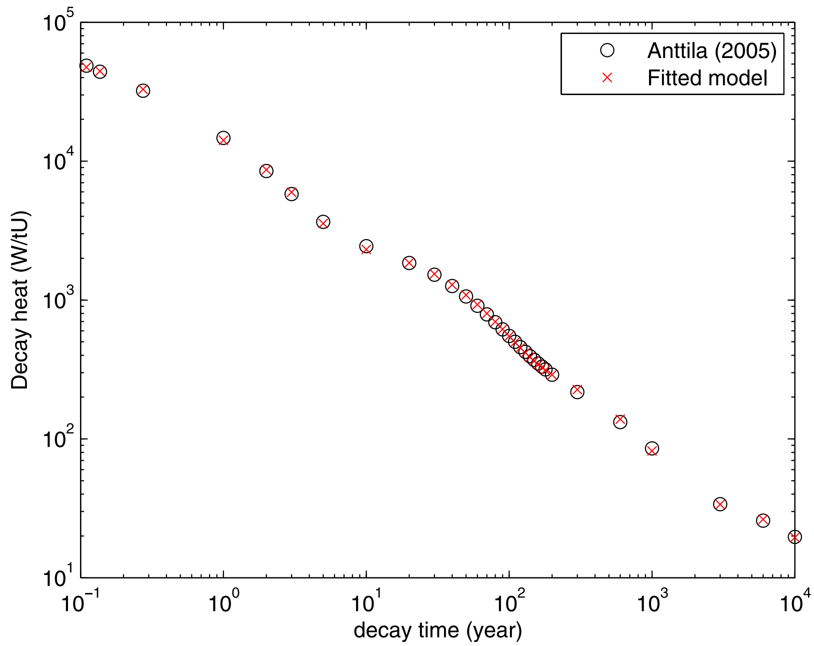

Fig. 4. Decay heat data (black circles) and statistical fit (red crosses).

$$[(p-w)q - W(S(T),M(T)) - K(T)]e^{-rT} + V_T(T)e^{-rT} - rV(T)e^{-rT} = 0, \tag{A.31}$$

from which the result follows.

A.7. Proof of Proposition 5

Eq. (A.31) can be rewritten as

$$[(p-w)q - W(S(T),M(T)) - K(T)] + V_T(T) - rV(T) = 0. \tag{A.32}$$

Assume that the second derivative of the objective function with respect to T, $\Sigma(T)$, is strictly negative at T^*. The implicit function theorem implies that

$$T_r(r) = \frac{V(T^*) + rV_r(T^*) - V_{Tr}(T^*)}{\Sigma(T^*)}, \tag{A.33}$$

where $V(T^*) + rV_r(T^*) - V_{Tr}(T^*)$ is the derivative of $rV(T^*) - V_T(T^*)$ with respect to r. Hence, if $\mathrm{d}/\mathrm{d}r(rV(T^*) - V_T(T^*)) < 0$, $T_r(r) > 0$, and if $\mathrm{d}/\mathrm{d}r(rV(T^*) - V_T(T^*)) > 0$, $T_r(r) < 0$, as required.

Differentiation of the payment function (7) with respect to r gives

$$P_r(r) = -V_T(T(r))T_r(r) - V_r(T(r)). \tag{A.34}$$

A.8. Proof of Proposition 6

Consider the problem in Eqs. (9)–(11) and denote $\Pi(t) := (p-w)q - W(S(t),M(t)) - K(t)$. Hamiltonian is

$$H(\theta,B,\eta,t) = \Pi(t)(1-\theta)e^{-rt} + \eta(rB + \theta\Pi(t)), \tag{A.35}$$

and the necessary conditions include the following[19]:

$$\theta = \begin{cases} 0 & \text{if } -\Pi e^{-rt} + \eta\Pi < 0, \\ \text{any } \theta \in [0,1] & \text{if } -\Pi e^{-rt} + \eta\Pi = 0, \\ 1 & \text{if } -\Pi e^{-rt} + \eta\Pi > 0, \end{cases} \tag{A.36}$$

$$\dot{B} = rB + \theta\Pi, \tag{A.37}$$

$$\dot{\eta} = -r\eta, \quad \eta(T) = \beta, \quad \beta \text{ is a constant}, \tag{A.38}$$

[19] Theorem 2 of Chapter 3 in Seierstad and Sydsæter (1987).

$$\Pi(T)(1-\theta(T))e^{-rT} + \eta(T)(rB(T) + \theta(T)\Pi(T)) + \beta V_T(T) = 0. \tag{A.39}$$

Clearly $\eta(t) = ke^{-rt}$ for some constant k. As $-\Pi e^{-rt} + \eta\Pi = e^{-rt}\Pi(k-1)$, $k < 1$ and (A.36) imply that $\theta = 0$ for all t and hence no money is deposited to the account and the constraints are violated. $k > 1$ implies that $\theta = 1$ for all t, which means that the total discounted profit for the firm is zero. Hence $k = 1$. As $\eta(t) = e^{-rt}$, $\beta = e^{-rT}$ and condition (A.36) implies that any payment function θ is optimal. Using Equation $B(T) = -V(T)$, Eq. (A.39) reduces then to

$$\Pi(T) - rV(T) + V_T(T) = 0. \tag{A.40}$$

This matches, after reorganization, the equation in Proposition 4, and therefore $T = T^*$.

Suppose the fee is given by a constant θ. The solution to Eq. (10) with the initial condition $B(0) = 0$ is

$$B(t) = e^{rt}\int_0^t \big((p-w)q - W(S(z),M(z)) - K(z)\big)\theta e^{-rz}\,\mathrm{d}z. \tag{A.41}$$

Evaluating this at $t = T^*$ and using $B(T^*) = -V(T^*)$ gives after slight manipulation equation

$$\theta\int_0^{T^*} \big((p-w)q - W(S(z),M(z)) - K(z)\big)e^{-rz}\,\mathrm{d}z = -V(T^*)e^{-rT^*}. \tag{A.42}$$

The result given in the proposition follows from this.

A.9. Decay estimation

The decay heat generation data for spent nuclear fuel of an EPR reactor was obtained from (Anttila, 2005, page 303). Although planned burnup in OL3 is less than 50 MWd/kgU, we use decay heat data for burnup of 60 MWd/kgU, which has been a design criteria for Finnish encapsulation plant (Raiko, 2012, page 131). The data consists of decay heat generation, as a function of time, when the fuel is removed from the reactor at time zero. We utilize data from 0.1 years to 10 000 years after the removal.

The data is presented in Fig. 4 by black circles. We identified five exponential decay modes and estimated their parameters using non-linear regression. The regression equation was

$$\log s_t = \log\left[\sum_{i=1}^{5}\alpha_i\exp(-\delta_i t)\right] + v_t, \tag{A.43}$$

where v_t is error term. The regression equation describes the decay of one unit of spent fuel, i.e., it describes the decay heat generation added to the heat generation stock in each moment of time. That is, the regression is made on $\lim_{T\to 0} S(t)/(qT)$, where $S(t)$ is given by Eq. (2). Hence, parameters α_i and δ_i have the usual amount of new heat generation and the decay rate interpretations, respectively (see Section 3).

The logarithmic transformation was used to balance the estimation to the whole data range. Without log-transformation, the estimation overemphasized the initial period of high heat generation. The fitted values are presented in Fig. 4 by red crosses. The fit is reasonably good over the whole data range. The five mode formulation of decay heat seems sufficient for the purposes of this paper.

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